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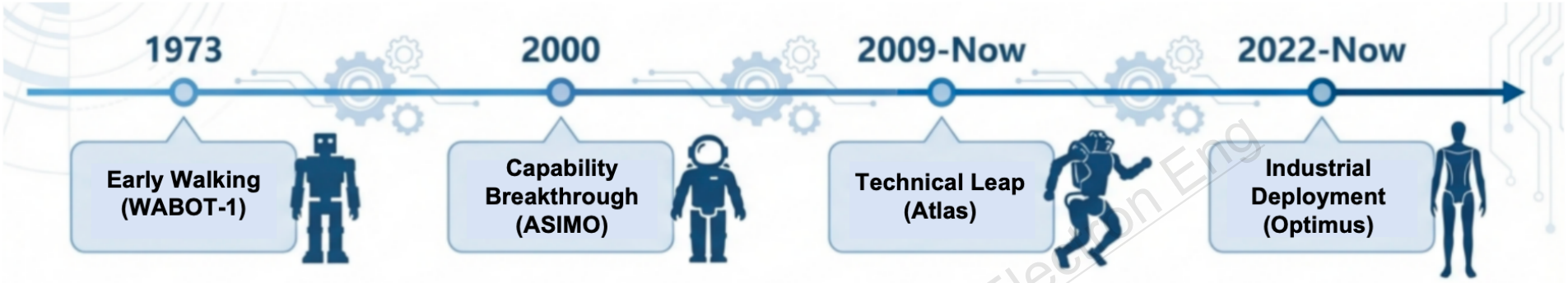
A comprehensive review on humanoid robots: perspectives from academia and industry

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Key words: Humanoid robots; Dual-perspective analysis; Industrial applications; Technical challenges; Future directions

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Humanoid robots: exploding yet fragmented



The Market Surge

Global Investment Growth (Estimated)



Drivers: Aging populations & labor shortages are transitioning robots from "Research Prototypes" to "Practical Assistants".

The Literature Gap



The Problem

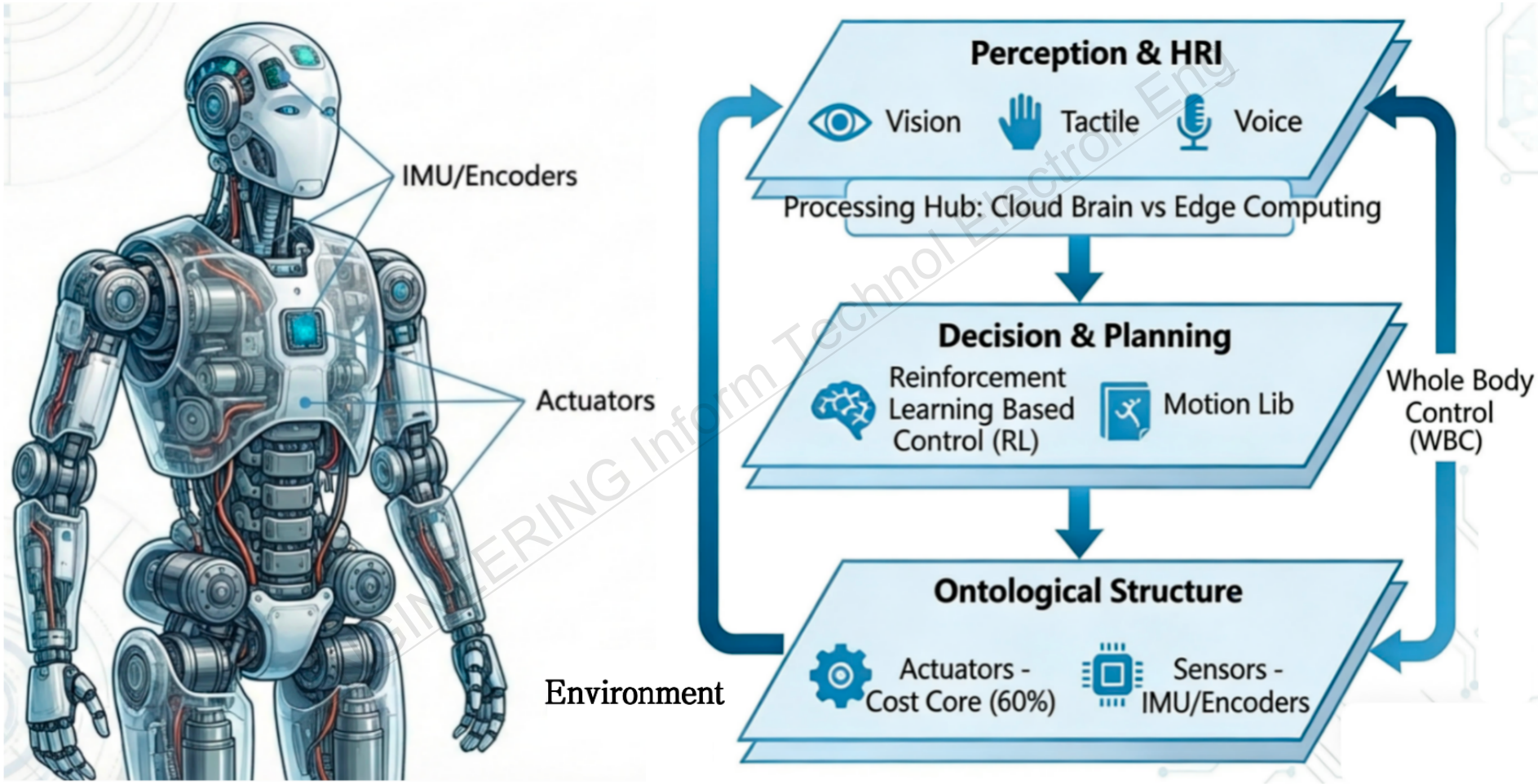
Existing reviews are fragmented and overly academic. They lack analysis of market dynamics, cost constraints, and Technology Readiness Levels (TRL).

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Our contributions

1) Comprehensive dual-perspective analysis 2) Extensive industrial product analysis
3) Systematic challenge–solution framework 4) Integrated technology assessment

Technical architecture: a closed-loop system of perception, decision-making, and control

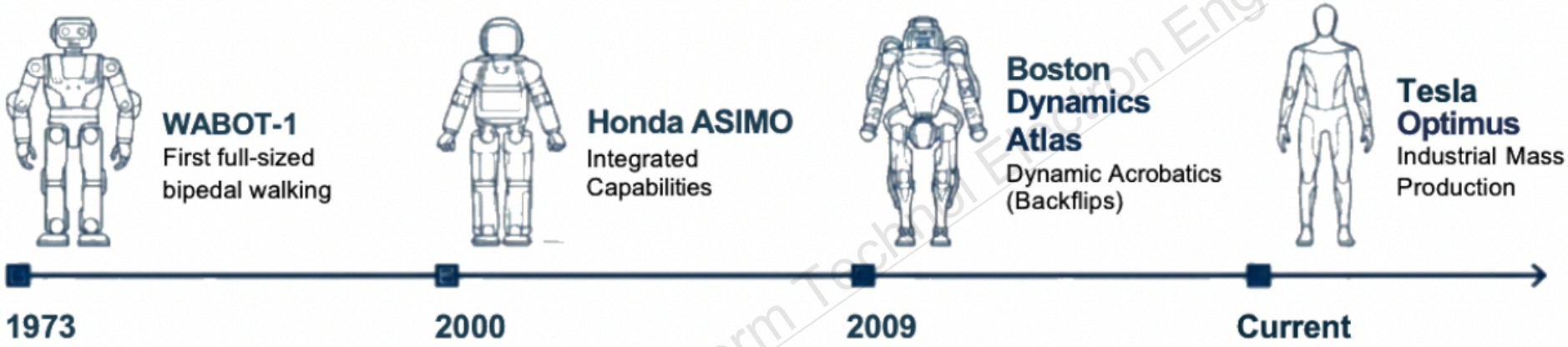


Key technologies

Hardware, perception & cognition, control & locomotion, and RI

State of the art: the academic perspective

☐ From model-based control to learning-based adaptation



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Main trends:

- **Control shift:** transition from model-based (ZMP) to learning-based (reinforcement learning/imitation learning)
- **Open collaboration:** the "Open X-embodiment" initiative (293 authors, over 1 million trajectories solving data scarcity)
- **Efficiency:** OpenVLA (7B parameters) outperforming larger models via better data efficiency

State of the art: the academic perspective

☐ Comparative analysis of market leaders

Tesla Optimus Gen2



Focus: Manufacturing

Spec: 172cm / 56kg

Key Tech: Tesla Autopilot Chips, Cost <$20k target.

Boston Dynamics Atlas



Focus: Dynamic Agility

Spec: 150cm / 89kg

Key Tech: Hydraulic Actuation, Heavy Payload.

Unitree H1



Focus: Speed & Power

Spec: 180cm / 47kg

Key Tech: High-torque M107 Motors, 3.3 m/s speed.

UBTECH Walker X



Focus: Service / Home

Spec: 130cm / 63kg

Key Tech: Safe HRI, Compliant Control.

Xiaomi CyberOne



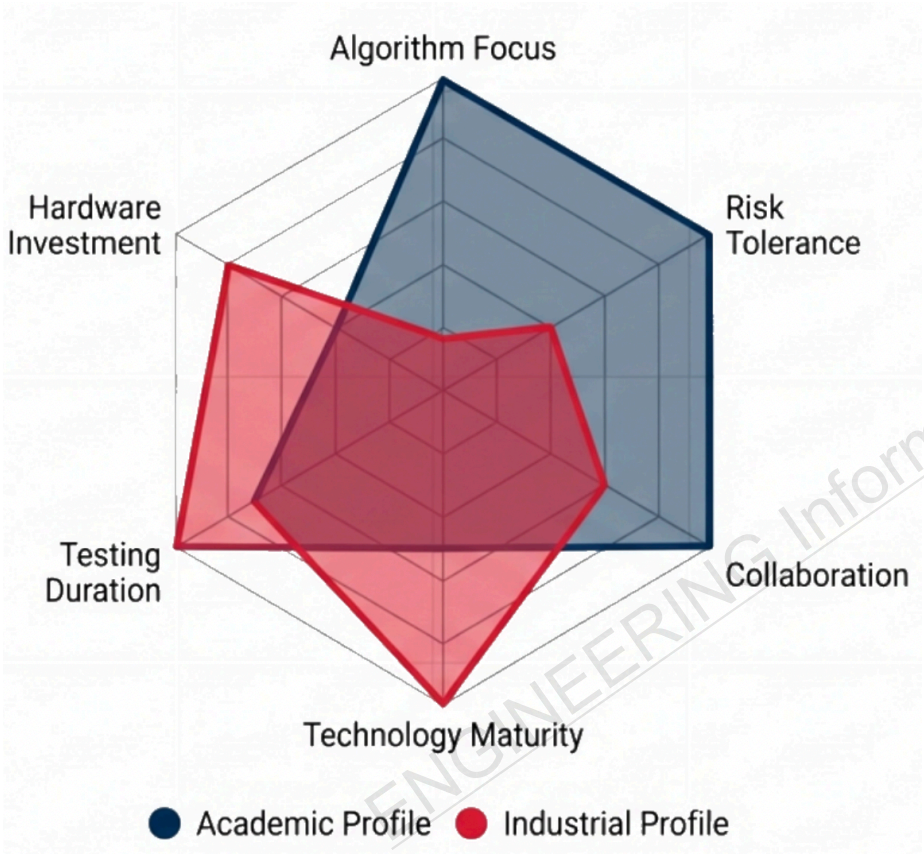
Focus: Interaction

Spec: 177cm / 52kg

Key Tech: Emotion Recognition (85 cues).

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Critical insight: the academic–industrial gap



The “Valley of Death” metrics

☐ **Technology readiness level (TRL):**

✓ Academia (TRLs 3–4: proof of concept)

✓ Industry (TRLs 8–9: qualified system)

☐ **Testing standards:**

✓ Academic prototypes (100–1000 h)

✓ Commercial requirements (MTBF>

✓ 10 000 h)

☐ **Intellectual property:**

✓ Open publication

✓ Patent protection (actuator patents dominate industry filings)

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Six major barriers to mass adoption

1 Hardware & Cost

Actuators are ~60% of total cost. Target: Reduce unit cost from >$150k to ~$20k.

2 Energy Constraints

AI GPUs (200-300W) drain standard batteries (1-2 kWh) too fast for sustained work.

3 Perception Limits

Trade-off between accuracy and speed. Visual/Tactile fusion is computationally expensive.

4 Control Complexity

Robust locomotion on uneven terrain (stairs, slopes) remains unstable under payload.

5 HRI Difficulties

Lack of 'Social Intelligence'. Difficulty understanding sarcasm, ambiguity, and cultural context.

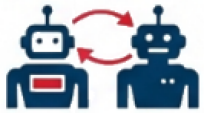
6 Ethics & Society

Job displacement risks (20-30% in manufacturing) and dual-use (weaponization) concerns.

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Promising research areas

1. Collaborative Intelligence



Multi-robot teams

2. Autonomy Enhancement



Causal Reasoning

3. Environmental Adaptation



Soft robotics/Morphology

4. HRI Optimization

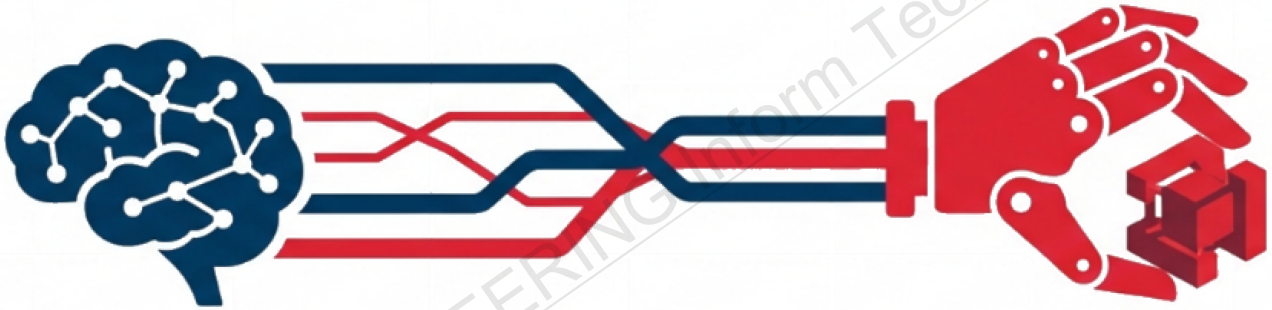


Affective computing

5. Cross-Domain Application



Disaster zones/Elderly care



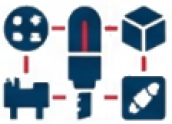
Large Language Models

Inter

Embodied Action

Inter

6. Infrastructure



Standardized modular components

7. Ethical Frameworks



Safety assurance

Key Shift: From **"Code-to-Walk"** to **"Language-to-Action"** end-to-end learning

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Future outlook

- This survey provides actionable guidance for advancing the field toward more capable, affordable, and socially-integrated humanoid robots.

Term	Outlook
Near-term (1–3 years)	Limited commercial deployment in controlled environments with improved actuator efficiency and foundation model integration
Medium-term (3–5 years)	Multi-robot collaboration breakthroughs and deployment in semi-structured environments with cost reductions via standardization
Long-term (5–10 years)	Truly autonomous humanoid robots operating in complex, unstructured environments with large-scale deployment across diverse applications

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Corresponding author biography



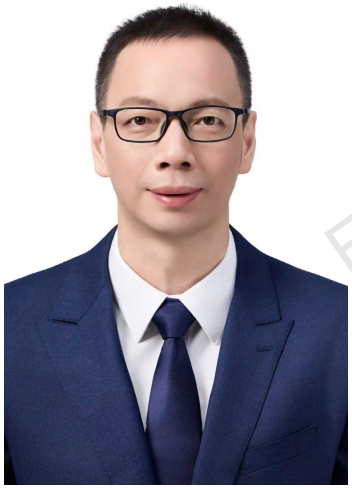
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